MULTI-PHASE ACCELERATION OF A DATA STORAGE DISC

by

Serge J. Fayeulle

MULTI-PHASE ACCELERATION OF A DATA STORAGE DISC

Related Applications

This application claims priority of United States provisional application Serial Number 60/277,763, entitled "Multi-Step Acceleration Method for CSS Applications," filed March 21, 2001.

Field of the Invention

This application relates generally to a data storage device and more particularly, but not limited to, a multi-phase acceleration procedure for rotating a data storage disc in a disc drive.

Background of the Invention

Modern hard disc drives comprise one or more rigid discs that are coated with a magnetizable medium and mounted on a spindle hub of a spindle motor for rotation at a high speed. Information is read from and written to each disc on a plurality of concentric tracks by a read/write head mounted on an actuator arm. The outside circumference of each disc is referred to as the "outer diameter" (OD), and the center of each disc is referred to as the "inner diameter" (ID). A read/write head is said to "fly" over the disc surface as the disc rotates. When disc rotational velocity decreases, the layer of air supporting the read/write head above the disc surface diminishes and the head descends toward the disc surface. Contact between the read/write head and the disc surface can damage the magnetizable medium and the head. Furthermore, through a phenomenon called "stiction," a read/write head can become temporarily "stuck" to the disc surface after landing on the disc surface. Stiction can damage the magnetizable medium, the read/write head, and/or the actuator arm when the disc drive system initiates disc rotation in an attempt to move the read/write head from the disc surface.

-2-

A conventional contact-start-stop (CSS) solution may be used to address this problem. In a disc drive system utilizing a CSS interface, a read/write head lands and is parked on a textured landing zone, preferably near the ID of the disc, as the disc loses rotational velocity and eventually completes spinning. Typically, data is not recorded in the landing zone, and the texturing of the landing zone surface minimizes stiction. The read/write head is moved from the landing zone and back to data areas on the disc when the rotational velocity increases to allow the head to fly above the disc surface.

In order to decrease flying height and increase aerial density, conventional CSS solutions have moved toward the use of a padded slider taking off and landing in a laser textured landing zone with lower laser bumps. However, such an implementation is not without problems. For instance, the padded slider solutions result in high friction forces during contact between the slider and the landing zone. Furthermore, a padded slider may result in excessive wear of the coating on the disc. Yet another problem associated with padded sliders concerns normal wear, and thus maintenance of, the padded slider pads. Excessive wear of both the coatings on the discs and the pads on the sliders may lead to premature failure and crash of the head media interface. Wear of the slider pads may also result in an increase of stiction between the slider and the disc surface.

Summary of the Invention

Against this backdrop the present invention has been developed. The present invention is a multi-phase acceleration procedure for rotating a disc in a disc drive. More particularly, the multi-phase acceleration procedure rotates the disc from an initial rotational velocity (V_i) to a final rotational velocity (V_F) over a predetermined time period (T_F-T_i). The multi-phase acceleration procedure applies multiple acceleration steps, rates or phases to the disc to initiate rotation by the disc at an initial time (T_i) and set the rotational velocity of the disc at the final rotational velocity (V_F). Predetermined constraints and parameters, such as the initial rotational velocity (V_i), the time (T_i) at which the disc is spinning at the initial rotational velocity (V_i), the final rotational velocity (V_F) of the disc and the time (T_F) at which the disc reaches final rotational velocity (V_F), may be defined to be any value or range of values, depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

In accordance with an embodiment, the multi-phase acceleration procedure may be utilized in creating and maintaining an air bearing between a slider of a read/write head and the disc surface as the read/write head accesses tracks on the disc surface in response to a read/write instruction. As such, the final rotational velocity (V_F) may be defined as a velocity sufficient to maintain the air bearing as the read/write head radially traverses across the disc between an inner diameter of the disc and an outer diameter. As the disc reaches the final rotational velocity (V_F), the read/write head may be moved from a landing zone to one or more data zones on the disc. By accelerating the disc at multiple acceleration phases, friction forces between the slider and the surface of the disc may be minimized or completely eliminated, thereby reducing wear on both the landing zone surface and the slider.

In accordance with another embodiment, the multi-phase acceleration procedure may accelerate the disc at multiple acceleration rates based on predetermined time periods between an initial time parameter (T_i) and a final time parameter (T_F). As such, the disc may be accelerated at a first acceleration rate from time T_i to a predefined time parameter (T_N), but accelerated at a second acceleration rate from time T_N to the time T_F. Time T_F may correspond to a time that the rotational velocity of the disc has reached a velocity sufficient to create and maintain an air bearing between a slider of the head and the surface of the disc as the head radially traverses across the disc between the inner diameter and the outer diameter. Thus, the read/write head may be moved from the landing zone to one or more data zones on the disc at time T_F.

In accordance with another embodiment, the multi-phase acceleration procedure may be used as the read/write head exits the landing zone and enters one or more data regions on the disc as the disc is rotating at a rotational velocity that is less than the final rotational velocity (V_F). As such, the read/write head may exit the landing zone as the disc reaches a desired early exit velocity (V_D). Although the desired early exit velocity (V_D) is a velocity sufficient to create the air bearing between the slider and the surface of the disc as the head is situated in close proximity to the inner diameter, the desired early exit velocity (V_D) may be insufficient to maintain the air bearing as the head traverses toward the outer diameter. Thus, the multi-phase acceleration procedure may accelerate the disc at one or more acceleration rates after the head has exited the landing zone in order to maintain the air bearing as the head is moved across the disc toward the outer diameter.

The present invention also can be implemented as a computer-readable program storage device which tangibly embodies a program of instructions executable by a computer system to accelerate a data storage disc at multiple acceleration rates to attain a final rotational velocity of the rotating disc.

These and various other features as well as advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of the Drawings

FIG. **1** is a plan view of a disc drive incorporating a preferred embodiment of the present invention showing the primary internal components.

FIG. **2** is a functional block diagram generally showing the main functional components used to control the disc drive of FIG. **1**.

FIG. **3** is a plan view of a disc generally showing the main components on the surface of the disc in accordance with an embodiment of the present invention.

FIG. **4** is a graphical representation of friction force evolution as rotational velocity of a disc is increased from an initial velocity to a final rotational velocity at a constant acceleration.

FIG. **5** is a graphical representation illustrating a change in rotational velocity over time as the disc of FIG. **4** is subjected to a constant acceleration between the initial velocity and the final velocity.

FIG. **6** is a graphical representation illustrating a change in rotational velocity over time as a disc is subjected to multiple phases of acceleration in accordance with an embodiment of the present invention.

FIG. **7** is a graphical representation of friction force evolution as rotational velocity of a disc is increased from an initial velocity to a final rotational velocity at a constant acceleration, such as the constant acceleration depicted in FIG. **5**, and at multiple phases of acceleration in accordance with an embodiment of the present invention.

FIG. **8** is a flow diagram that illustrates operational characteristics of a multi-phase acceleration procedure in accordance with an embodiment of the present invention.

FIG. **9** is a flow diagram that illustrates operational characteristics shown in FIG. **8** in more detail in accordance with an embodiment of the present invention.

-5-

FIG. **10** is a flow diagram that illustrates operational characteristics of a multi-phase acceleration procedure utilizing an early exit technique for accessing tracks on a data storage disc in accordance with an alternative embodiment of the present invention.

Detailed Description

5   The present invention and its various embodiments are described in detail below with reference to the figures. When referring to the figures, like structures and elements shown throughout are indicated with like reference numerals.

A disc drive **100** constructed in accordance with a preferred embodiment of the present invention is shown in FIG. **1**. The disc drive **100** includes a base **102** to which various components of the disc drive **100** are mounted. A top cover **104**, shown partially cut away, cooperates with the base **102** to form an internal, sealed environment for the disc drive **100** in a conventional manner. The components include a spindle motor **156** (FIG. **2**) which rotates a spindle hub **106** and one or more discs **108** attached to the hub **106** at a constant high speed. A magnetic media disc **108** is used to illustrate a preferred embodiment of the present invention, but

15   the present invention may be implemented using other types of data storage discs. Information is written to and read from tracks **306** (FIG. **3**) on the discs **108** through the use of an actuator assembly **110**, which rotates about a bearing shaft assembly **112** positioned adjacent to the discs **108**. The actuator assembly **110** includes a plurality of actuator arms **114** which extend towards the discs **108**, with one or more flexures **116** extending from each of the actuator arms **114**.

20   Mounted at the distal end of each of the flexures **116** is a transducer, or read/write head **118**, which includes an air bearing slider (not shown) enabling the read/write head **118**, to fly in close proximity above the corresponding surface of the associated disc **108**.

The spindle motor **156** is typically de-energized when the disc drive **100** is not in use for extended periods of time. In accordance with an embodiment of the present invention, the

25   read/write heads **118** may be moved over park, or landing, zones **120** near the inner diameter (ID) **136** of the discs **108** when the drive motor **156** is de-energized. The read/write heads **118** may be secured over the landing zones **120** through the use of an actuator latch arrangement (not shown), which prevents inadvertent rotation of the actuator assembly **110** when the heads **118** are parked. This latch arrangement is typically a magnetic latch which magnetically holds the actuator

30   assembly **110** against a stop. Although the landing zone **120** is shown in FIG. **1** as located in

close proximity to the inner diameter 136 of the discs 108, a landing zone 120 may also be located in close proximity to an outer diameter (OD) 138 of the discs 108. Furthermore, a landing zone 120 may be located on any portion of the discs 108 between the outer diameter 138 and the inner diameter 136 of the discs 108.

The radial position of the heads 118 is controlled through the use of a voice coil motor (VCM) 124, which typically includes a coil 126 attached to the actuator assembly 110, as well as one or more permanent magnets 128 which establish a magnetic field in which the coil 126 is immersed. The controlled application of current to the coil 126 causes magnetic interaction between the permanent magnets 128 and the coil 126 so that the coil 126 moves in accordance with the well-known Lorentz relationship. As the coil 126 moves, the actuator assembly 110 pivots about the bearing shaft assembly 112 and the heads 118 are caused to move across the surfaces of the discs 108.

A flex assembly 130 provides the requisite electrical connection paths for the actuator assembly 110 while allowing pivotal movement of the actuator assembly 110 during operation. The flex assembly 130 includes a printed circuit board 132 to which head wires (not shown) are connected; the head wires being routed along the actuator arms 114 and the flexures 116 to the heads 118. The printed circuit board 132 typically includes circuitry for controlling the write currents applied to the heads 118 during a write operation and for amplifying read signals generated by the heads 118 during a read operation. The flex assembly terminates at a flex bracket 134 for communication through the base deck 102 to a disc drive printed circuit board (not shown) mounted to the bottom side of the disc drive 100.

Referring now to FIG. 2, shown therein is a functional block diagram of the disc drive 100 shown in FIG. 1 generally showing the main functional circuits which are resident on the disc drive printed circuit board and used to control the operation of the disc drive 100. The disc drive 100 is shown in FIG. 2 to be operably connected to a host computer 140 in which the disc drive 100 is mounted in a conventional manner. Control communication paths are provided between the host computer 140 and a disc drive microprocessor 142, the microprocessor 142 generally providing top level communication and control for the disc drive 100 in conjunction with programming for the microprocessor 142 stored in microprocessor memory (MEM) 143. The MEM 143 can include random access memory (RAM), read only memory (ROM), and other sources of resident memory for the microprocessor 142. The discs 108 are rotated on the spindle

hub 106 at a constant high speed by a spindle motor 156 that is controlled by a spindle control

module 148. The spindle control module 148 is a component of an application specific integrated

chip (ASIC) 152 receiving instructions related to rotational velocity from the microprocessor

142. The microprocessor 142 sets the rotational velocity of the spindle hub 106, and thus the

5   discs 108 attached thereto, by communicating with the spindle control module 148. Accordingly,

the spindle control module 148 receives instructions from the microprocessor 142 directing the

control module 148 to set the rotational velocity of the discs 108.

Although the spindle control module 148 may be implemented as any type of hardware,

i.e. a digital or analog circuit, or software, i.e., machine or computer based programming

10   language, for illustration purposes and not by means of limitation, the spindle control module 148

is described hereafter as an analog circuit. As such, once the spindle control module 148 is

instructed of the desired rotational speed of the discs 108 via communication with the

microprocessor 142, the spindle control module 148 supplies current to windings (not shown) of

the spindle motor 156. Current supplied to the windings may be generated from a power supply,

15   such as a battery source, and regulated by the spindle control module 148 such that the magnitude

of the current dictates the rotational speed of the discs 108 attached to the spindle hub 106. The

spindle motor 156 may be a "Y" type brushless, three-phase spindle motor 156 having fixed

windings (not shown) as field coils in accordance with one embodiment of the present invention.

As such, the spindle control module 148 serves as a power supply to the spindle motor 156 by

20   generating a current through the windings (not shown) of the motor 156.

The radial position of the heads 118 over the rotating discs 108 is controlled through the

application of current to a coil 126 of the VCM 124. A servo control system 150 provides such

control. Like the spindle control module 148, the servo control system 150 is a component of the

ASIC 152 and thus receives instructions from the microprocessor 142. In executing a read or

25   write command, the microprocessor 142 receives servo information identifying the position of

the read/write head 118 on the disc 108. Based on this servo information, the microprocessor 142

instructs the servo control system 150 of the displacement needed in order for the head 118 to

seek from an origination track 306 associated with the current head position to a destination track

306. The servo control system 150 then supplies a current to the coil 126 of the VCM 124 based

30   on the instruction from the microprocessor 142. The controlled application of current to the coil

126 causes magnetic interaction between the permanent magnets 128 (FIG. 1) and the coil 126 so

that the coil **126** moves in accordance with the well-known Lorentz relationship. As the coil **126** moves, the actuator arms **114** about the bearing shaft assembly **112** and the heads **118** are caused to move across the surfaces of the rotating discs **108**.

Data is transferred between the host computer **140** and the disc drive **100** by way of a disc drive interface **144**, which includes a buffer **145** to facilitate high speed data transfer between the host computer **140** and the disc drive **100**. Data to be written to the discs **108** are thus passed from the host computer **140** to the buffer **145** and then to a read/write channel **146**, which encodes and serializes the data and provides the requisite write current signals to the heads **118**. To retrieve data that has been previously stored by the disc drive **100**, read signals are generated by the heads **118** and provided to the read/write channel **146**. The interface **144** performs read signal decoding, error detection, and error correction operations. The interface **144** then outputs the retrieved data to the buffer **145** for subsequent transfer to the host computer **140**. Such operations of the disc drive **100** are well known in the art and are discussed, for example, in U.S. Pat. No. 5,276,662 issued Jan. 4, 1994, to Shaver et al.

At disc drive power down, the microprocessor **142** transmits a signal to the spindle control module **148** instructing the module **148** to discontinue the application of current to the windings (not shown) of the spindle motor **156**. The spindle control module **148** may include circuitry, such as relays, solid-state switches, such as a field effect transistor (FET), or other switching device to open-circuit the output lines of the spindle control module **148** to the spindle motor **156** thereby disconnecting the spindle control module **148** from the spindle motor **156**. The spindle hub **106**, and thus the discs **108** rotating around the spindle hub **106**, immediately begin to lose rotational velocity as the discs **108** continue spinning due to rotational inertia in the discs **108**.

At disc drive power down, in order to prevent the heads **118** from contacting the data zones or regions **304** (FIG. 3) on the surface of the discs **108**, the servo control system **150** directs the read/write heads **118** to a location away from the data zones **304** of the disc. In accordance with an embodiment of the present invention, this location may be a landing zone **120** in close proximity to the ID **136** of the discs. In accordance with other embodiments, a landing zone **120** may be located in close proximity to the OD **138** of the discs **108** or on a region between the OD **138** and the ID **136**.

Regardless of the position of the landing zones **120** on the surface of the discs **108**, the landing zones **120** may be either non-textured, i.e., smooth surface, or laser-textured. Likewise, the read/write heads **118** may contain textured or non-textured sliders (not shown). A specific interface between a disc **108** and a read/write head **118** may be defined based on the

5   configuration, i.e., textured or non-textured, of the disc **108** and the slider of the head **118**. For example, a LAP interface (Laser Assisted Pad) may be defined as a configuration having a laser-textured disc surface and a textured, or padded, slider. A laser-texture zone (LZT) interface may be defined as a configuration having a laser-textured disc surface and a non-textured, or non-padded, slider. A SLIP interface (Slider Landing Integrated Pad) may be defined as a

10   configuration having a non-textured disc surface and a textured, or padded, slider. In accordance with various embodiments of the present invention, the disc drive **100** may contain LAP, LZT or SLIP interfaces between the heads **118** and discs **108**.

Although FIGS. **3**, **4**, **5**, **6**, **7**, **8**, **9** and **10** are hereafter described with reference to a single disc **108**, which only has a single type of interface, the disc drive **100** may contain any number of

15   discs **108**, with each disc **108** having any type of interface, such as a SLIP interface, a LAP interface or an LZT interface. As such, a disc drive **100** may include a first disc **108** having an LAP interface between the disc **108** and an associated read/write head **118**, a second disc **108** having an LAP interface between the disc **108** and an associated read/write head **118** and a third disc **108** having an LZT interface between the disc **108** and an associated read/write head **118**.

20   Furthermore, the two surfaces of each disc **108** may have separate types of interfaces between the surfaces of the disc **108** and an associated read/write head **118**. As such, it is possible for a top surface of a disc **108** to have a SLIP interface between the disc **108** and an associated read/write head **118** and a bottom surface of the same disc **108** to have an LZT interface between the disc **108** and an associated read/write head **118**.

25   FIG. **3** shows the logical recording structure of an exemplary disc **108** of the disc drive **100**. The disc **108** is divided into several concentric data zones **304** which contain regions of adjacent tracks **306**. For example, the magnetic disc **108** of FIG. **3** includes an inner zone **308**, a center zone **311**, and an outer zone **312**. When configured with servo burst sectors **314**, each disc track **306** is divided into slices called data wedges **316**. The burst sectors **314** include data for

30   maintaining accurate positioning of the disc head **118** and are positioned in predetermined locations along the disc **108**. As the disc **108** rotates, the data head **118** reads the servo

information containing an address within the servo bursts **314** and sends the servo information

back to the servo control system **150**. The servo control system **150** checks whether the address

in the servo information read from the burst sectors **314** corresponds to the desired head location.

If the address does not correspond to the desired head location, the actuator arm **114** is adjusted

5   until the head **118** is moved to the correct track location.

Each track **306** includes discrete data sectors **322** containing stored user information. The

number of data sectors **322** contained in a particular track **306** depends, in part, on the length (i.e.,

circumference) of the track **306**. Therefore, tracks **306** located at the outer zone **312** typically

contain more data sectors **322** per data wedge **316** than tracks **306** located at the center zone **311**.

10   Similarly, tracks **306** located at the center zone **311** typically contain more data sectors **322** per

data wedge **316** than tracks **306** located at the inner zone **308**. Besides containing user

information, each data sector **322** also may include other data to help identify and process the

user information. Tracks **306** may also contain one or more permanently defective sectors **322**

that cannot be reliably written to or read from by the disc drive **100** circuitry. For this reason, a

15   number of alternate sectors are provided in one or more alternate tracks **320** to which data that is

intended to be written in these defective sectors can be revectored.

In accordance with an embodiment of the present invention, the disc **108** may include one

or more landing zones **120** for parking the read/write head **118** while the drive **100** is de-

energized. As such, the head **118** is prevented from inadvertently contacting the surface of the

20   disc **108** while the disc **108** is stationary. The use of a landing zone **120** to disengage a head **118**

from data regions on the surface of the disc **108** is commonly found in disc drives **100**

administering a contact start/stop (CSS) technique. With respect to the CSS technique, the servo

control system **150** controls the actuator **114** such that the slider (not shown) contacts the landing

zone **120** during start and stop operations when there is insufficient rotational speed to maintain

25   the air bearing between the surface of the disc **108** and the slider. As described above, the

landing zone **120** may be a dedicated radial region on the disc **108** that is specially textured to

minimize the effect of stiction, which is static friction between a very smooth disc surface and a

slider of a head **118**.

Referring to FIG. **4**, a graphical representation of friction force evolution as rotational

30   velocity of a disc **108** is increased from zero velocity to a final rotational velocity at a constant

acceleration. More specifically, FIG. **4** shows a graphical representation illustrating friction

forces associated with an LAP interface and an SLIP interface as the rotational velocity of a disc

108 increases at a constant acceleration over a given time period. Friction force is directly

correlated to friction energy, which is the energy dissipated in contact between the slider of the

read/write head **118** and the surface of the disc **108** mainly though heat generation and the wear

5   of materials. Thus, friction force may be defined as friction energy divided by contact length.

FIG. **5** depicts a graphical representation illustrating a change in rotational velocity over

time as the disc **108** of both the LAP interface and SLIP interface of FIG. **4** is subjected to the

constant acceleration. As such, FIGS. **4** and **5** are described below in tandem. Friction forces

associated with a SLIP interface as rotational velocity of the disc **108** increases from an initial

10   velocity (V_i) of 0 revolutions/second to a final rotational velocity (V_F) at the constant acceleration

is shown by a SLIP plot **400**. Likewise, friction forces associated with an LAP interface as the

rotational velocity of the disc **108** increases from an initial velocity (V_i) of 0 revolutions/second

to the final velocity (V_F) at a constant acceleration is shown by an LAP plot **402**. With respect to

both the SLIP plot **400** and the LAP plot **402**, friction forces are measured between an initial time

15   (T_i) and a final time (T_F), wherein the initial time (T_i) represents the beginning of disc rotation

and the final time (T_F) represents a desired time at which the rotational velocity of the disc **108**

reaches the final velocity (V_F). As an example, and not a means of limitation, the time for the

disc **108** to reach the final rotational velocity (V_F) is described and shown in FIGS. **4** and **5** as 4

seconds. Thus, the initial time (T_i) is 0 seconds and the final time (T_F) is 4 seconds. However, it

20   should be appreciated that predetermined constraints and parameters, such as the time (T_F) for a

disc to reach final velocity (V_F), may be defined to be any value or range of values, depending on

any number of factors, including, but not limited to, disc drive design and operating

specifications.

Referring to FIG. **5,** as the spindle control module **148** receives instructions from the

25   microprocessor **142** to excite rotation by the spindle hub **106**, and thus the disc **108** attached

thereto, a current is applied to the windings (not shown) of the spindle motor **156** thereby

initiating rotation of the disc **108**. Thus, time 0 seconds of FIG. **5** represents a point in time that

disc rotation is initiated, thus, the rotational velocity of the disc **108** is the initial velocity (V_i).

The rotational velocity of the disc **108** is then accelerated at a constant acceleration for 4 seconds

30   to the final velocity (V_F). As such, a plot **500** shows a constant increase in velocity from 0

seconds to 4 seconds. Once the rotational velocity of the disc **108** reaches final rotational

velocity (V_F), the servo control system **150** moves the read/write head **118** from the landing zone **120** to a data region **304** on the disc **108**. As such, the final velocity (V_F) is preferably defined as a velocity sufficient to create and maintain an air bearing between the slider of the read/write head **118** and the surface of the disc **108** as the head **118** accesses the surface of the disc **108** between the ID **136** and the OD **138**.

In accordance with an alternative embodiment, which may be referred to as an "early exit technique," the read/write head **118** may exit the landing zone **120** at a time prior to the rotational velocity of the disc **108** reaching final rotational velocity (V_F). In disc drives **100** implementing the early exit technique, the servo control system **150** moves the read/write head **118** from the landing zone **120** to a data region on the disc **108** at a desired early exit velocity (V_D). The desired early exit velocity (V_D) may preferably be a velocity sufficient to create an air bearing between the slider of the head **118** and the surface of the disc **108** as the head **118** is in close proximity to the ID **136**. However, the desired early exit velocity (V_D) is typically insufficient to maintain the air bearing between the slider and the surface of the disc **108** as the head **118** moves toward the OD **138** due to an increasing large circumference that the head **118** must track as it moves toward the OD **138**. Hence, the acceleration of the rotational velocity must be such that the rotational velocity of the disc **108** increases at a rate sufficient to maintain the air bearing as the head **118** moves toward the OD **138** from an early exit time (V_D) to the final time (V_F) corresponding to the time (T_F) that the disc **108** reaches final rotational velocity (V_F).

As an example, and not a means of limitation, the final rotational velocity (V_F) may be defined as 7200 revolutions/second. Hence, taking the change in velocity (ΔV), which is defined as V_i subtracted from V_F, over the change in time (ΔT), which is 4 seconds, the acceleration applied to the disc **108** is defined at 1800 revolutions/second^2. As such, if the disc **108** is rotated at an acceleration of 1800 revolutions/second^2, after 4 seconds the disc **108** rotates at 7200 revolutions/second and the servo control system **150** moves the head **118** from the landing zone **120** to a data region **304** as an air bearing is already defined between the surface of the disc **108** and the slider due to the rotational velocity of the disc **108**.

If the disc drive **100** utilizes the early exit technique, the disc drive **100** is preferably designed such that rotation of the disc **108** is increased at a greater acceleration as compared to a disc drive **100** not implementing the early exit technique. For instance, if the servo control system **150** moves the head **118** from the landing zone **120** to a data region **304** at a time

-13-

corresponding to 3000 revolutions/second, the head **118** may reach the OD **138** prior to 4

seconds. As such, disc drive designers must increase the rate of acceleration to ensure that the

rotational velocity maintains the air bearing as the head **118** sweeps across the disc towards the

OD **138**. As an example, and not a means of limitation, the projected time that the head **118**

reaches the OD **138** may be 3 seconds. If the rotational velocity needed to maintain the air

bearing as the head **118** is in close proximity to the OD **138** is 7200 revolutions/second, then the

constant acceleration applied to the disc **108** is preferably 2400 revolutions/second^2.

Referring to FIG. **4**, the SLIP plot **400** shows that, for a padded slider-smooth disc

configuration, after a first phase **404** of rapid increase and decrease in friction forces, a second

phase **406** occurs where friction first increases then decreases slowly. This second phase **406** is

primarily due to contact of the trailing edge of the slider when the pitch angle is increased

because of the increasing rotational velocity of the disc **108**. Referring to the LAP plot **402**,

although a second phase **406** of friction increase is not seen as a padded slider takes off from a

textured disc surface, a first phase **404** of friction forces actually last longer in time than the

increase realized with the SLIP interface. Whereas the forces shown by the SLIP plot **400**

decrease from approximately 4 grams to approximately 2 grams after .25 seconds, forces shown

by the LAP plot **402** remain at approximately 4 grams until approximately .45 seconds. As such,

applying a constant acceleration to the rotating disc **108** results in undesirable friction forces

between the slider, whether padded or non-padded, and the landing zone **120** surface, whether

textured or non-textured. In accordance with an embodiment of the invention, multiple

acceleration phases may be applied to a disc **108** between an initial time (T_i) of zero velocity and

a final time (T_F) corresponding to a final rotational velocity (V_F). By accelerating the disc **108** at

multiple acceleration rates, disc rotation is initiated at the initial time (T_i) and the rotational

velocity of the disc **108** is increased at the multiple acceleration rates until the rotational velocity

of the disc **108** reaches the final velocity (V_F). Such a multi-stage acceleration procedure

eliminates the second phase **406** of friction forces and reduces the length in time that friction

forces are realized between the slider and the disc surface as the disc **108** rotates between the

initial time (T_i) and the final time (T_F).

FIG. **6** depicts a graphical representation illustrating a change in rotational velocity over

time as a disc **108** is subjected to multiple phases, rates, stages or steps of acceleration in

accordance with an embodiment of the present invention. As such, FIG. **6** shows a multi-phase

acceleration procedure for rotating a disc **108** at multiple acceleration rates in accordance with an embodiment of the present invention. The disc drive **100** is designed such that final rotational velocity (V_F) is attained in the rotating disc **108** at a predetermined final time (T_F). Thus, the time for the disc **108** to reach the final rotational velocity (V_F) is described and shown in FIG. **6** as the final time (T_F) in seconds. Whereas the final time (T_F) is preferably a predetermined time constant, the initial time (T_i) is preferably 0 seconds. As an example, and not a means of limitation, the final time (T_F) is hereafter described in FIG. **6** as 4 seconds and the corresponding final rotational velocity (V_F) is described as 7200 revolutions/second. However, it should be appreciated that predetermined constraints and parameters, such as final rotational velocity of the disc **108** and the time (T_F) at which the disc **108** reaches final rotational velocity (V_F), may be defined to be any value or range of values, depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

As the spindle control module **148** receives instructions from the microprocessor **142** to excite rotation by the spindle hub **106**, and thus the disc **108** attached thereto, a current is applied to the windings (not shown) of the spindle motor **156** thereby initiating rotation of the disc **108**. Thus, time 0 seconds of FIG. **6** represents a point in time that disc rotation is initiated, thus, the rotational velocity of the disc **108** is an initial rotational velocity (V_i). The rotational velocity of the disc **108** is then accelerated at a first acceleration rate **602** from the initial rotational velocity (V_i) to a first velocity (V_1). As such, a plot **600** shows a constant increase in velocity from T_i seconds to T_1 seconds. The rate of acceleration may be determined by dividing the change in rotational velocity of the disc **108** by the time period associated with the velocity change (assuming a constant acceleration). Thus, the first acceleration rate **602** may be defined by the following equation:

$$a_1 = \Delta V/\Delta T = (V_1 - V_i)/(T_1 - T_i) \; [revs/s^2]$$

As an example to illustrate FIG. **6**, and not a means of limitation, the first velocity (V_1) may be defined at 3000 revolutions/second and T_1 may be predetermined at 1 second. Thus, the first acceleration rate **602** (a_1) is defined as 3000 revs/s^2.

After the rotational velocity of the disc **108** reaches the first velocity (V_1), which according to the example is 3000 revolutions/second, the spindle control module **148** changes the rate of acceleration of the spindle hub **106**, and thus the discs **108** rotating thereto, to a second acceleration rate **604** in accordance with an embodiment of the present invention. Specifically,

the disc **108** is then accelerated at a second acceleration rate **604** from the first velocity (V_1) to a second velocity (V_N). As such, a plot **600** shows a constant increase in velocity from T_1 seconds to T_N seconds. As mentioned above, the rate of acceleration may be determined by dividing the change in rotational velocity of the disc **108** by the time period associated with the velocity change. Thus, the second acceleration rate **604** may be defined by the following equation:

$$a_2 = \Delta V/\Delta T = (V_N - V_1)/(T_N - T_1) \ [revs/s^2]$$

To further illustrate the above example, and not a means of limiting the present invention, the second velocity (V_N) may be defined at 5000 revolutions/second and T_N may be predetermined at 2 seconds. Thus, the second acceleration rate **604** (a_2) is defined as 2000 revs/s².

After the rotational velocity of the disc **108** reaches the second velocity (V_N), which according to the example is 5000 revolutions/second, the spindle control module **148** may change the rate of acceleration of the spindle hub **106**, and thus the discs **108** rotating thereto, to a third acceleration rate **606** in accordance with an embodiment of the present invention. Specifically, the disc **108** is then accelerated at a third acceleration rate **606** from the second velocity (V_N) to a third velocity (V_{N+1}). As such, a plot **600** shows a constant increase in velocity from T_N seconds to T_{N+1} seconds. As mentioned above, the rate of acceleration may be determined by dividing the change in rotational velocity of the disc **108** by the time period associated with the velocity change. Thus, the third acceleration rate **606** may be defined by the following equation:

$$a_3 = \Delta V/\Delta T = (V_{N+1} - V_N)/(T_{N+1} - T_N) \ [revs/s^2]$$

To further illustrate the above example, and not a means of limiting the present invention, the third velocity (V_{N+1}) may be defined at 6200 revolutions/second and T_{N+1} may be predetermined at 3 seconds. Thus, the third acceleration rate **606** (a_3) is defined as 1200 revs/s².

After the rotational velocity of the disc **108** reaches the final velocity (V_{N+1}), which according to the example is 6200 revolutions/second, the spindle control module **148** may yet further change the rate of acceleration of the spindle hub **106**, and thus the discs **108** rotating thereto, to a fourth and final acceleration rate **608** in accordance with an embodiment of the present invention. Specifically, the disc **108** is then accelerated at a fourth acceleration rate **608** from the third velocity (V_{N+1}) to a fourth velocity (V_F), which in accordance with the example of FIG. **6** is also the final rotational velocity. As such, a plot **600** shows a constant increase in velocity from T_{N+1} seconds to T_F seconds. As mentioned above, the rate of acceleration may be

-16-

determined by dividing the change in rotational velocity of the disc **108** by the time period

associated with the velocity change. Thus, the fourth acceleration rate **608** may be defined by the

following equation:

$$a_4 = \Delta V/\Delta T = (V_F - V_{N+1})/(T_F - T_{N+1}) \text{ [revs/s}^2]$$

5   To further illustrate the above example, and not a means of limiting the present invention,

the fourth velocity (V_F) may be defined at 7200 revolutions/second and T_F may be predetermined

at 4 seconds. Thus, the fourth and final acceleration rate **608** (a_4) is defined as 1000 revs/s^2.

After the rotational velocity of the disc **108** reaches the final velocity (V_F), which

according to the example of FIG. **6** is a predetermined final rotational velocity of 7200

10   revolutions/second, the servo control system **150** moves the read/write head **118** from the landing

zone **120** to a data region **304** on the disc **108** in accordance with an embodiment of the present

invention. Although the multi-phase acceleration procedure is shown in and illustrated in FIG. **6**

as applying four acceleration rates (**602, 604, 606** and **608**) to the disc **108** to achieve a final

rotational velocity by the disc **108**, and thus a final rotational velocity (V_F) being derived at the

15   termination of the fourth acceleration rate **608**, it should be appreciated that the multi-phase

acceleration procedure may use only two acceleration rates, with the final rotational velocity (V_F)

of the disc **108** being realized at the termination of the second of the two acceleration rates.

Equally important, the multi-phase acceleration procedure may also apply any number of

acceleration rates to the disc **108** to achieve the final rotational velocity (V_F), so long as at least 2

20   acceleration rates are used.

The final rotational velocity (V_F) is preferably defined as a velocity sufficient to create

and maintain an air bearing between the slider of the read/write head **118** and the surface of the

disc **108** as the head **118** accesses the surface of the disc **108** between the ID **136** and the OD **138**.

Because the final rotational velocity (V_F) occurs at a predetermined time (T_F) following a

25   predetermined number of acceleration rates, movement of the head **118** from the landing **120** to a

data region **304** between the ID **136** and the OD **138** may be triggered based on either a velocity

parameter (V_F) or a timing parameter (T_F) in accordance with various embodiments of the present

invention.

In accordance with an alternative embodiment implementing the "early exit technique,"

30   the read/write head **118** may exit the landing zone **120** at a time prior to the rotational velocity of

the disc **108** reaching the final velocity (V_F). In disc drives **100** implementing the early exit

technique, the servo control system **150** moves the read/write head **118** from the landing zone **120** to a data region **304** on the disc **108** at a desired early exit velocity (V_D). Because the early exit velocity (V_D) occurs at a predetermined time (T_D) following a predetermined number of acceleration rates, movement of the head **118** from the landing **120** to a data region **304** between the ID **136** and the OD **138** may be triggered based on a velocity parameter (V_D) or a timing parameter (T_D), which may be referred to as an early exit time. The early exit velocity (V_D) may preferably be a velocity sufficient to create an air bearing between the slider on the read/write head **118** and the surface of the disc **108** as the head **118** is located in close proximity to the ID **136**. However, because the early exit velocity (V_D) is typically insufficient to maintain the air bearing between the slider and the surface of the disc **108** as the head **118** moves toward the OD **138**, the acceleration rates applied to the rotating disc **108** must be such that the rotational velocity increases at a rate sufficient to maintain the air bearing as the head **118** moves toward the OD **138** from the early exit time (T_D) to the final time (T_F) corresponding to the time that the disc **108** reaches final rotational velocity (V_F).

Referring to FIG. **7**, a graphical representation of friction force evolution as rotational velocity of a disc **108** is increased from an initial velocity (V_i) of 0 revolutions/second to a final rotational velocity (V_F). More specifically, FIG. **7** shows two graphical representations illustrating friction forces over time as rotational velocity of a disc **108** increases both at a constant acceleration (plot **702**) and at multiple acceleration phases (plot **700**). Friction forces associated with a SLIP interface as rotational velocity of a disc **108** increases from zero velocity (V_i) to the final rotational velocity (V_F) at multiple acceleration phases in accordance with an embodiment of the present invention is shown by a first SLIP plot **700**. Likewise, friction forces associated with a SLIP interface as the rotational velocity of a disc **108** increases from zero velocity (V_i) to the final rotational velocity (V_F) at a constant acceleration is shown by a second SLIP plot **702**.

With respect to both the first SLIP plot **700** and the second SLIP plot **702**, friction forces are measured between an initial time (T_i) and a final time (T_F), wherein the initial time (T_i) represents the beginning of disc rotation and the final time (T_F) represents a desired time at which the rotational velocity of the disc **108** reaches a final rotational velocity (V_F) sufficient to maintain an air bearing between the slider of the head **118** and the surface of the disc **108** as the head **118** moves toward the OD **138**. As an example, and not a means of limitation, the time (T_F)

for the disc **108** to reach the final rotational velocity (V_F) is described and shown in FIG. **7** as 8 seconds. Thus, the initial time (T_i) is 0 seconds and the final time (T_F) is 8 seconds. However, it should be appreciated that predetermined constraints and parameters, such as the final rotational velocity (V_F) and the time (T_F) for a disc to reach final rotational velocity (V_F), may be defined to be any value or range of values, depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

Referring to FIG. **7**, the second SLIP plot **702** shows that, for a padded slider-smooth disc configuration, after a first phase **704** of rapid increase and decrease of friction forces, a second phase **706** occurs where the friction forces first increase then decrease slowly. This second phase is primarily due to contact of the trailing edge of the slider when the pitch angle is increased because of the increasing rotational velocity of the disc **108**. As shown by the first SLIP plot **700**, by applying multiple acceleration phases to the disc **108** between an initial time (T_i) and a final time (T_F), the second phase of friction forces between the slider of the head **118** and the surface of the landing zone **120** is eliminated. Furthermore, applying multiple acceleration phases to the rotating disc **108** results in a shorter time period at which friction forces are realized between the slider and the landing zone **120** surface, as shown by the difference in the first phase **704** of friction forces between the two plots **700** and **702**. Whereas the forces shown by the first SLIP plot **700** decrease from approximately 4.2 grams to approximately 2 grams after .25 seconds, the forces shown by the second SLIP plot **702** remain at approximately 4 grams until approximately .6 seconds. Although not shown, application of multiple acceleration phases to a disc **108** from an initial rotational velocity (V_i) of zero revolutions/second to a final rotational velocity (V_F) in disc drives **100** utilizing an LAP and an LZT interface eliminates any potential second phases of friction force and reduces the length in time that friction forces are realized between the slider and the disc surface in a manner substantially similar to that described in FIG. **7**.

In accordance with an embodiment, the present invention may be implemented as a computer-readable program storage device which tangibly embodies a program of instructions executable by a computer system to accelerate a data storage disc **108** at multiple acceleration rates to attain a final rotational velocity (V_F) of the rotating disc **108**. As such, the logical operations of the various embodiments of the present invention may be implemented (1) as a sequence of computer implemented acts or program modules running on a computing system

and/or (2) as interconnected machine logic circuits or circuit modules within the computing system. The implementation is a matter of choice dependent on the performance requirements of the computing system implementing the invention. Accordingly, the logical operations making up the embodiments of the present invention described herein are referred to variously as operations, structural devices, acts or modules. It will be recognized by one skilled in the art that these operations, structural devices, acts and modules may be implemented in software, in firmware, in special purpose digital logic, and any combination thereof without deviating from the spirit and scope of the present invention as recited within the claims attached hereto.

FIG 8 illustrates operations associated with a multi-phase acceleration procedure 800 for rotating a disc 108 from an initial rotational velocity (V_i) to a threshold velocity (V_{TH}). Specifically, the multi-phase acceleration procedure 800 applies multiple acceleration steps, rates or phases to a disc 108 to initiate rotation by the disc 108 at an initial time (T_i) and set the rotational velocity of the disc 108 at a predetermined threshold rotational velocity (V_{TH}) from an initial rotational velocity of zero revolutions/second in accordance with an embodiment of the present invention. The multi-phase acceleration procedure 800 preferably accelerates the disc 108 at multiple acceleration rates such that the threshold rotational velocity (V_{TH}) is realized at a predetermined threshold time (T_{TH}). In accordance with an embodiment, the threshold velocity (V_{TH}) is a velocity sufficient to create an air bearing between a read/write head 118 and a surface of the disc 108 as the head 118 exits a landing zone 120 and enters a data region 304 on the surface of the disc 108. As such, the threshold velocity (V_{TH}) may be a final velocity (V_F) in accordance with one embodiment of the present invention or a desired early exit velocity (V_D) in accordance with an alternative embodiment of the present invention. As shown in more detail in FIG. 9, if the threshold velocity (V_{TH}) is a final velocity (V_F), the threshold velocity (V_{TH}) is a velocity sufficient to create and maintain the air bearing as the head 118 radially traverses across the disc 108 toward the outer diameter 138. In contrast, if the threshold velocity (V_{TH}) is a desired early exit velocity (V_D), the threshold velocity (V_{TH}) is typically a velocity sufficient only to create, but not maintain, the air bearing as the head 118 radially traverses across the disc 108 toward the outer diameter 138. Thus, the multi-phase acceleration procedure shown and illustrated in FIG. 10 describes continuing acceleration of the disc 108 past the threshold velocity (V_{TH}) in order to guarantee that air bearing is maintained as the head 118 continues toward the outer diameter 138.

-20-

The multi-phase acceleration procedure **800** comprises an operation flow beginning with a start operation **802** and concluding with a termination operation **814**. Specifically, the multi-phase acceleration procedure **800** is initiated at the start operation **802** as a computer microprocessor **142** transmits a read/write instruction to a servo control system **150** and a spindle control module **148**. The read/write instruction directs the spindle control module **148** to begin spinning one or more discs **108** to which data is to be written to or read from a read/write head **118** controlled by the servo control system **150**. For simplicity, the multi-phase acceleration procedure **800** is described below with reference to a single disc **108** of a disc drive **100**.

Operation flow passes from the start operation **802** to a receive operation **804**. The receive operation **804** receives the read/write instruction issued by the microprocessor **142**. After the read/write instruction is received, operation flow passes to an initial accelerate operation **806**. The initial accelerate operation **806** accelerates the disc **108** at an initial acceleration rate from an initial rotational velocity (V_i), which in accordance with an embodiment is zero revolutions/second, until the disc **108** reaches a first rotational velocity (V_1). As the disc **108** reaches the first rotational velocity (V_1), operation flow passes to a next accelerate operation **808**. The next accelerate operation **808** accelerates the disc **108** at a second acceleration rate until the disc **108** reaches a second rotational velocity (V_N). As the disc **108** reaches the second rotational velocity (V_N), operation flow passes to a velocity determine operation **810**. The velocity determine operation **810** determines whether the current rotational velocity of the disc **108** has reached the threshold rotational velocity (V_{TH}). The threshold rotational velocity (V_{TH}) may be defined to be any value or range of values depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

If the velocity determine operation **810** determines that the current rotational velocity is the desired final rotational velocity (V_F), operation flow passes to a head exit operation **812**. The head exit operation **812** moves the read/write head **118** from a landing zone **120** to a data region **304** on the surface of the disc **108** such that the head **118** may access, i.e., write to or read from, tracks **306** on the disc **108**. As described above and in more detail below, the head **118** may exit the landing zone **120** at either a final velocity (V_F) or a desired early exit velocity (V_D). As such, the tracks **306** on the disc **108** accessible by the head **118** depend on whether the head **118** exits the landing zone **120** at a final rotational velocity (V_F) or an early exit velocity (V_D). If the head **118** exits at a final velocity (V_F) then all tracks **306** on the disc **108** are accessible to the head **118**.

-21-

In contrast, less than all tracks **306** on the disc are accessible to the head **118** if the head exits at an early exit velocity (V_D).

If the velocity determine operation **810** determines that the current rotational velocity is not the predetermined threshold velocity (V_{TH}), operation flow passes back to the next accelerate operation **808**. The disc **108** is then accelerated at an acceleration rate different from the previous acceleration rate applied by next accelerate operation **808** and operation flow continues passing between the next accelerate operation **808** and the velocity determine operation **810** until the threshold rotational velocity (V_{TH}) is realized. After the read/write head **118** is moved from the landing zone **120**, operation flow concludes at the termination operation **814**.

FIG. 9 illustrates operations associated with a multi-phase acceleration procedure **900** for rotating a disc **108** from an initial rotational velocity (V_i) to a final rotational velocity (V_F) over a predetermined time period (T_F-T_i) in accordance with an embodiment of the present invention. Specifically, the multi-phase acceleration procedure **900** applies multiple acceleration steps, rates or phases to a disc **108** to initiate rotation by the disc **108** at an initial time (T_i) and set the rotational velocity of the disc **108** at a predetermined final velocity (V_F). Thus, the threshold velocity (V_{TH}) described in FIG. **9** is a predetermined final velocity (V_F). The multi-phase acceleration procedure **900** preferably accelerates the disc **108** at multiple acceleration rates such that the final rotational velocity (V_F) is realized at a predetermined final time (T_F). The rotational velocity of the disc **108** is preferably 0 revolutions/second at the initial time (T_i). Predetermined constraints and parameters, such as the initial rotational velocity (V_i), and the time (T_i) at which disc rotation is initiated, the final rotational velocity (V_F) and the time (T_F) at which the disc **108** reaches final rotational velocity (V_F), may be defined to be any value or range of values, depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

The multi-phase acceleration procedure **900** comprises an operation flow beginning with a start operation **902** and concluding with a termination operation **924**. Specifically, the multi-phase acceleration procedure **900** is initiated at the start operation **902** as a computer microprocessor **142** transmits a read/write instruction to a servo control system **150** and a spindle control module **148**. The read/write instruction directs the spindle control module **148** to begin spinning one or more discs **108** to which data is to be written to or read from a read/write head

118 controlled by the servo control system **150**. For simplicity, the multi-phase acceleration procedure **900** is described below with reference to a single disc **108** of a disc drive **100**.

Operation flow passes from the start operation **902** to a receive operation **904**. The receive operation **904** receives the read/write instruction issued by the microprocessor **142**. After the read/write instruction is received, operation flow passes to an initial accelerate operation **906**. The initial accelerate operation **906** accelerates the disc **108** at an initial acceleration rate from an initial rotational velocity (V_i), which in accordance with an embodiment is zero revolutions/second, until the disc **108** reaches a first rotational velocity (V_1). In accordance with an embodiment of the present invention, the disc **108** reaches the first rotational velocity (V_1) following an initial predetermined time period following the initial time (T_i). The initial predetermined time period preferably ends at time T_1. As such, operation flow passes from the initial accelerate operation **906** to a first query operation **908**. The first query operation **908** determines whether the disc **108** has been rotating for the initial predetermined time period by comparing the current time of disc rotation to time T_1. If the current time does not equal time T_1, operation flow passes back to the initial accelerate operation **906** and rotation of the disc **108** is continued at the initial acceleration rate until time T_1. At time T_1, operation flow passes to a next accelerate operation **910**.

The next accelerate operation **910** accelerates the disc **108** at a second acceleration rate different from the initial acceleration rate until the disc **108** reaches a next rotational velocity (V_N). In accordance with an embodiment of the present invention, the disc **108** reaches the next rotational velocity (V_N) following a second predetermined time period beginning at time T_1 and ending at a time T_N. As such, operation flow passes from the next accelerate operation **910** to a second query operation **912**. The second query operation **912** determines whether the disc **108** has been rotating for the second predetermined time period by comparing the current time of disc rotation to time T_N. If the current time does not equal time T_N, operation flow passes back to the next accelerate operation **910** and rotation of the disc **108** is continued at the second acceleration rate until time T_N. At time T_N, operation flow passes to a third query operation **914**.

The third query operation **914** determines whether the current rotational velocity of the disc **108** has reached a predetermined final rotational velocity (V_F) by comparing the length of the current time period of disc rotation from the initial velocity (V_i) to a predetermined final time period. The predetermined final time period preferably ends at time T_F. In accordance with an

embodiment of the present invention, the time T_F may be predetermined as a time at which the rotational velocity of the disc **108** is sufficient to create and maintain an air bearing between the slider of the read/write head **118** and the surface of the disc **108** as the head **118** accesses the surface of the disc **108** between the ID **136** and the OD **138**. Moreover, the final rotational velocity (V_F) and time T_F may be defined to be any value or range of values depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

If the third query operation **914** determines that the length of the current time period equals the predetermined final time period, operation flow passes to a head exit operation **916**. The head exit operation **916** moves the read/write head **118** from a landing zone **120** to a data region **304** on the surface of the disc **108** such that the head **118** may access, i.e. write to or read from, tracks **306** on the disc **108**. Once the head **118** is moved to a data region **304**, operation flow concludes with a terminate operation **924**. If, however, the third query operation **914** determines that the length of the current time period does not equal the predetermined final time period, operation flow passes to a subsequent accelerate operation **920**. The subsequent accelerate operation **920** accelerates the disc **108** at a third acceleration rate different from the second acceleration rate applied by the next accelerate operation **910**. Subsequent accelerate operation **920** accelerates the disc **108** until the disc **108** reaches a next rotational velocity (V_{N+1}). In accordance with an embodiment of the present invention, the disc **108** reaches the next rotational velocity (V_{N+1}) following a third predetermined time period beginning at time T_N and ending at a time T_{N+1}. As such, operation flow passes from the subsequent accelerate operation **920** to a fourth query operation **922**.

The fourth query operation **922** determines whether the current time is time T_{N+1}. If the current time is not time T_{N+1}, operation flow passes back to the subsequent accelerate operation **920** and rotation of the disc **108** is continued at the third acceleration rate until time T_{N+1}. At time T_{N+1}, operation flow passes to the third query operation **914** and continues to the head exit operation **916** if the current time equals time T_F. If, however, the disc **108** has not been rotating for the final predetermined time period ending at time T_F, operation flow passes back to the subsequent accelerate operation **920** and continues as previously described. Each instance that operation flow passes to subsequent accelerate operation **920** from the third query operation **914**, the subsequent accelerate operation **920** accelerates the disc **108** at an acceleration rate different from the previously applied acceleration rate. As such, the subsequent accelerate operation **920**

-24-

may accelerate the disc 108 at a third, fourth, fifth, sixth, etc.... acceleration rate, with each
acceleration rate being different in magnitude than the previous acceleration rate, e.g., the fifth
acceleration rate is preferably different than the fourth acceleration rate, but the sixth acceleration
rate may be the same magnitude as the third acceleration rate. For clarity and operational flow
purposes, the acceleration rate applied by the subsequent acceleration operation 920 is hereafter
referred to as a "next acceleration rate" in order to distinguish the rate from the acceleration rates
applied by the operation 920 on previous operation flow passes. Operation flow continues
passing between the subsequent accelerate operation 920, the fourth query operation 922 and the
third query operation 914 until the third query operation 914 determines that the disc 108 has
been rotating for the predetermined final time period ending at time T_F, at which time, operation
flow passes to the head exit operation 916 and continues as described above.

FIG. 10 illustrates operations associated with a multi-phase acceleration procedure 1000
for rotating a disc 108 from an initial rotational velocity (V_i) to a final rotational velocity (V_F)
over a predetermined time period (T_i-T_F) in accordance with an alternative embodiment of the
present invention. The multi-phase acceleration procedure 1000 applies multiple acceleration
steps, rates, stages or phases to a disc 108 to initiate rotation by the disc 108 at an initial time (T_i)
and set the rotational velocity of the disc 108 at a predetermined final rotational velocity (V_F).
The multi-phase acceleration procedure 1000 preferably accelerates the disc 108 at multiple
acceleration rates such that final rotational velocity (V_F) is realized at a predetermined final time
(T_F). The rotational velocity of the disc 108 is preferably zero revolutions/second at the initial
time (T_i). The multi-phase acceleration procedure 1000 is a multi-phase acceleration procedure,
such as the procedure 900 in FIG. 9, incorporating operations associated with an early exit
technique moving a read/write head 118 from a landing zone 120 to a data region 304 on the disc
108 at a desired early exit velocity (V_D). Thus, the threshold velocity (V_{TH}) described in FIG. 10
is a desired early exit velocity (V_D). Predetermined constraints and parameters, such as the
desired early exit velocity (V_D), the final rotational velocity (V_F) of the disc 108 and the time (T_F)
at which the disc 108 reaches both the desired early exit velocity (V_D) and final rotational
velocity (V_F), may be defined to be any value or range of values, depending on any number of
factors, including, but not limited to, disc drive design and operating specifications.

The multi-phase acceleration procedure 1000 comprises an operation flow beginning with
a start operation 1002 and concluding with a termination operation 1024. Specifically, the multi-

phase acceleration procedure **1000** is initiated at the start operation **1002** as a computer

microprocessor **142** transmits a read/write instruction to a servo control system **150** and a spindle

control module **148**. The read/write instruction directs the spindle control module **148** to begin

spinning one or more discs **108** to which data is to be written to or read from by a read/write head

5   **118** controlled by the servo control system **150**. For simplicity, the multi-phase acceleration

procedure **1000** is described below with reference to a single disc **108** of a disc drive **100**.

Operation flow passes from the start operation **1002** to a receive operation **1004**. The

receive operation **1004** receives the read/write instruction issued by the microprocessor **142**.

After the read/write instruction is received, operation flow passes to an initial accelerate

10   operation **1006**. The initial accelerate operation **1006** accelerates the disc **108** at an initial

acceleration rate from an initial rotational velocity (V_i), which in accordance with an embodiment

is zero revolutions/second, until the disc **108** reaches a first rotational velocity (V_1). In

accordance with an embodiment of the present invention, the disc **108** reaches the first rotational

velocity (V_1) following an initial predetermined time period following the initial time (T_i). The

15   initial predetermined time period preferably ends at time T_1. Operation flow simultaneously

passes from the initial accelerate operation **1006** to a first query operation **1008** and a velocity

query operation **1015**. The first query operation **1008** determines whether the disc **108** has been

rotating for the initial predetermined time period by comparing the current time of disc rotation to

time T_1. If the current time does not equal time T_1, operation flow passes back to the initial

20   accelerate operation **1004** and rotation of the disc **108** is continued at the initial acceleration rate

until time T_1.

The velocity query operation **1015** determines whether the rotational velocity of the disc

108 has reached the desired early exit velocity (V_D). If the velocity query operation **1015**

determines that the early exit velocity (V_D) has been reached, operation flow passes to an early

25   exit operation **1017**. The early exit operation **1017** moves the read/write head **118** from a landing

zone **120** to a data region **304** on the surface of the disc **108** such that the head **118** may access,

i.e. write to or read from, tracks **306** on the disc **108**. Although the desired early exit velocity

(V_D) may preferably be a velocity sufficient to create and maintain an air bearing between the

slider of the head **118** and the surface of the disc **108** as the head **118** is in close proximity to the

30   ID **136**, the desired early exit velocity (V_D) is typically a velocity insufficient to maintain the air

bearing between the slider and the surface of the disc **108** as the head **118** moves toward the OD

138. This circumstance is primarily due to an increasing large circumference that the head 118 must track as it moves toward the OD 138. Hence, operation flow passes from the early exit operation 1017 to the first query operation 1008 to guarantee that the rotational velocity of the disc 108 increases at a rate sufficient to maintain the air bearing as the head 118 moves toward the OD 138. Operation flow then continues to the query operation 1008 and continues passing between the query operation 1008 and the initial accelerate operation 1006 until time T_1.

If, however, the velocity query operation 1015 determines that the early exit velocity (V_D) has not been reached, operation flow passes to the first query operation 1008 without passing to the early exit operation 1017 and continues passing between the initial accelerate operation 1006, the first query operation 1008 and the velocity query operation 1015 until time T_1. Regardless of whether the head 118 has been moved from the landing zone 120 to the data region 304, at time T_1 operation flow passes to a next accelerate operation 1010.

The next accelerate operation 1010 accelerates the disc 108 at a second acceleration rate different from the initial acceleration rate until the disc 108 reaches a next rotational velocity (V_N). In accordance with an embodiment of the present invention, the disc 108 reaches the next rotational velocity (V_N) following a second predetermined time period beginning at time T_1 and ending the time T_N. Operation flow simultaneously passes from the next accelerate operation 1010 to a second query operation 1012 and the velocity query operation 1015. The second query operation 1012 determines whether the disc 108 has been rotating for the second predetermined time period by comparing the current time of disc rotation to time T_N. If the current time does not equal time T_N, operation flow passes back to the next accelerate operation 1010 and rotation of the disc 108 is continued at the second acceleration rate until time T_1.

The velocity query operation 1015 determines whether the rotational velocity of the disc 108 has reached the desired early exit velocity (V_D). If the velocity query operation 1015 determines that the early exit velocity (V_D) has been reached, operation flow passes to the early exit operation 1017. As described above, the early exit operation 1017 moves the read/write head 118 from a landing zone 120 to a data region 304 on the surface of the disc 108 such that the head 118 may access, i.e. write to or read from, tracks 306 on the disc 108. Although the desired early exit velocity (V_D) may preferably be a velocity sufficient to create and maintain an air bearing between the slider of the head 118 and the surface of the disc 108 as the head 118 is in close proximity to the ID 136, the desired early exit velocity (V_D) is typically a velocity insufficient to

maintain the air bearing between the slider and the surface of the disc **108** as the head **118** moves toward the OD **138**. This circumstance is primarily due to an increasing large circumference that the head **118** must track as it moves toward the OD **138**. Hence, operation flow passes from the early exit operation **1017** to the second query operation **1012** to guarantee that the rotational

5   velocity of the disc **108** increases at a rate sufficient to maintain the air bearing as the head **118** moves toward the OD **138**. Operation flow then continues to the second query operation **1012** and continues passing between the second query operation **1012** and the next accelerate operation **1010** until time T_N.

If, however, the velocity query operation **1015** determines that the early exit velocity (V_D)

10 has not been reached, operation flow passes to the second query operation **1012** without passing to the early exit operation **1017** and continues passing between the next accelerate operation **1010**, the second query operation **1012** and the velocity query operation **1015** until time (T_N). Regardless of whether the head **118** has been moved from the landing zone **120** to the data region **304**, at time T_N operation flow passes to a third query operation **1014**.

15   The third query operation **1014** determines whether the current rotational velocity of the disc **108** has reached the final rotational velocity (V_F) by comparing the length of the current time period of disc rotation from the initial velocity to a predetermined final time period ending at time T_F. In accordance with an embodiment of the present invention, the time T_F may be predetermined as a time at which the rotational velocity of the disc **108** is sufficient to create and

20   maintain an air bearing between the slider of the read/write head **118** and the surface of the disc **108** as the head **118** accesses the surface of the disc **108** between the ID **136** and the OD **138**. Moreover, the final rotational velocity (V_F) and time T_F may be defined to be any value or range of values depending on any number of factors, including, but not limited to, disc drive design and operating specifications.

25   If the third query operation **1014** determines that the length of the current time period equals the predetermined final time period, operation flow passes to a head exit operation **1016**. The head exit operation **1016** moves the read/write head **118** from a landing zone **120** to a data region **304** on the surface of the disc **108** such that the head **118** may access, i.e. write to or read from, tracks **306** on the disc **108**. Because the disc **108** is spinning at the final rotational velocity

30   (V_F) at time T_F, the air bearing is maintained between the head **118** and any location between the

-28-

ID 136 and the OD 138 on the disc 108. Once the head 118 is moved to a data region 304, operation flow concludes with a terminate operation 1024.

If, however, the third query operation 1014 determines that the length of the current time period does not equal the predetermined final time period (T_F), operation flow passes to a subsequent accelerate operation 1020. The subsequent accelerate operation 1020 accelerates the disc 108 at a third acceleration rate different from the second acceleration rate applied by next accelerate operation 1010. The subsequent accelerate operation 1020 accelerates the disc 108 until the disc 108 reaches a next rotational velocity (V_{N+1}). In accordance with an embodiment of the present invention, the disc 108 reaches the next rotational velocity (V_{N+1}) following a third predetermined time period beginning at time T_N and ending at a time T_{N+1}. Operation flow simultaneously passes from the subsequent accelerate operation 1020 to a fourth query operation 1022 and the velocity query operation 1015. The fourth query operation 1022 determines whether the disc 108 has been rotating for the third predetermined time period by comparing the current time of disc rotation to time T_{N+1}. If the current time does not equal time T_{N+1}, operation flow passes back to the subsequent accelerate operation 1020 and rotation of the disc 108 is continued at the third acceleration rate until time T_{N+1}.

The velocity query operation 1015 determines whether the rotational velocity of the disc 108 has reached the desired early exit velocity (V_D). If velocity query operation 1015 determines that the early exit velocity V_D has been reached, operation flow passes to the early exit operation 1017. As described above, the early exit operation 1017 moves the read/write head 118 from a landing zone 120 to a data region 304 on the surface of the disc 108 such that the head 118 may access, i.e. write to or read from, tracks 306 on the disc 108. Although the desired early exit velocity (V_D) may preferably be a velocity sufficient to create and maintain an air bearing between the slider of the head 118 and the surface of the disc 108 as the head 118 is in close proximity to the ID 136, the desired early exit velocity (V_D) is typically a velocity insufficient to maintain the air bearing between the slider and the surface of the disc 108 as the head 118 moves toward the OD 138. This circumstance is primarily due to an increasing large circumference that the head 118 must track as it moves toward the OD 138. Hence, operation flow passes from the early exit operation 1017 to the fourth query operation 1022 to guarantee that the rotational velocity of the disc 108 increases at a rate sufficient to maintain the air bearing as the head 118 moves toward the OD 138. Operation flow then continues to the fourth query operation 1022 and

continues passing between the fourth query operation **1022** and the subsequent accelerate operation **1020** until time T_{N+1}.

If, however, the velocity query operation **1015** determines that the early exit velocity (V_D) has not been reached, operation flow passes to the fourth query operation **1022** without passing to early exit operation **1017** and continues passing between the subsequent accelerate operation **1020**, the fourth query operation **1022** and the velocity query operation **1015** until time T_{N+1}. Regardless of whether the head **118** has been moved from the landing zone **120** to the data region **304**, at time T_{N+1} operation flow passes to the third query operation **1014**.

At time T_{N+1}, operation flow passes to the third query operation **1014** and continues to the head exit operation **1016** if the length of the current time period equals the predetermined final time period ending at time T_F. If, however, the disc **108** has not been rotating for the final predetermined time period ending at time T_F, operation flow passes back to the subsequent accelerate operation **1020** and continues as previously described. Each instance that operation flow passes to the subsequent accelerate operation **1020** from the third query operation **1014**, the subsequent accelerate operation **1020** accelerates the disc **108** at an acceleration rate different from the previously applied acceleration rate. As such, the subsequent accelerate operation **1020** may accelerate the disc **108** at a third, fourth, fifth, sixth, etc.... acceleration rate, with each acceleration rate being different in magnitude than the previous acceleration rate, e.g., the fifth acceleration rate is preferably different than the fourth acceleration rate, but the sixth acceleration rate may be the same magnitude as the third acceleration rate. For clarity and operational flow purposes, the acceleration rate applied by the subsequent acceleration operation **1020** is hereafter referred to as a "next acceleration rate" in order to distinguish the rate from the acceleration rates applied by the operation **1020** on previous operation flow passes. Operation flow continues passing between the subsequent accelerate operation **1020**, the velocity query operation **1015**, the fourth query operation **1022** and the third query operation **1014** until the third query operation **1014** determines that the disc **108** has been rotating for the predetermined final time period ending at time T_F, at which time, operation flow passes to the head exit operation **1016** and continues as described above.

In summary, the present invention may be viewed as a method (such as in operation **800**) for increasing rotational velocity of a data storage disc (such as **108**) in a disc drive (such as **100**). The method (such as in operation **800**) includes steps of accelerating (such as in operation **806**)

the data storage disc (such as **108**) at a first acceleration rate from an initial rotational velocity to a first predetermined rotational velocity, accelerating (such as in operation **808**) the data storage disc (such as **108**) at a second acceleration rate from the first predetermined rotational velocity to a threshold rotational velocity, and, as the data storage disc (such as **108**) rotates at the threshold

5   rotational velocity, moving (such as in operation **812**) a transducer (such as **118**) from a landing zone (such as **120**) to a data region (such as **304**) on a surface of the data storage disc (such as **108**). The threshold rotational velocity creates and maintains an air bearing between the transducer (such as **118**) and the surface of the disc (such as **108**).

In accordance with an embodiment, the threshold rotational velocity may be a final

10   rotational velocity creating and maintaining the air bearing as the transducer (such as **118**) radially traverses across the disc (such as **108**) between an inner diameter (such as **136**) and an outer diameter (such as **138**). As such, the accelerating step (such as in operation **808**) may include steps of accelerating (such as in operation **910**) the data storage disc (such as **108**) at the second acceleration rate from the first predetermined rotational velocity to a second

15   predetermined rotational velocity and accelerating (such as in operation **920**) the data storage disc (such as **108**) at one or more next acceleration rates from the second predetermined rotational velocity to the threshold rotational velocity if the second predetermined rotational velocity does not equal the threshold rotational velocity. The accelerating step (such as in operation **806**) may include accelerating the data storage disc (such as **108**) at the first acceleration rate between an

20   initial time corresponding to when the rotational velocity of the disc (such as **108**) equals the initial rotational velocity and a first predetermined time corresponding to when the rotational velocity of the disc (such as **108**) reaches the first predetermined rotational velocity. Likewise, the accelerating step (such as in operation **806**) may include accelerating the data storage disc (such as **108**) at the second acceleration rate between the first predetermined time and a threshold

25   time corresponding to when the rotational velocity of the disc (such as **108**) reaches the threshold rotational velocity. As such, the moving step (such as in operation **812**) may include a step of displacing the transducer (such as **118**) from the landing zone (such as **120**) at the threshold time.

In accordance with an alternative embodiment, the threshold rotational velocity may be an early exit velocity creating the air bearing as the transducer (such as **118**) exits the landing zone

30   (such as **120**) and accesses the data region (such as **304**). As such, the method (such as in operation **800**) may include a step of accelerating (such as in operation **1010** or **1020**) the data

storage disc (such as **108**) at a third acceleration rate from the threshold rotational velocity to a final rotational velocity. The final rotational velocity maintains the air bearing as the transducer (such as **118**) radially traverses toward an outer diameter (such as **138**) of the data storage disc (such as **108**). The accelerating step (such as in operation **806**) may include accelerating (such as in operation **1006**) the data storage disc (such as **108**) at the first acceleration rate between an initial time corresponding to when the rotational velocity of the disc (such as **108**) equals the initial rotational velocity and a first predetermined time corresponding to when the rotational velocity of the disc (such as **108**) reaches the first predetermined rotational velocity. Likewise, the accelerating step (such as in operation **808**) may include accelerating (such as in operation **1010**) the data storage disc (such as **108**) at the second acceleration rate between the first predetermined time and a threshold time corresponding to when the rotational velocity of the disc (such as **108**) reaches the threshold rotational velocity. As such, the moving step (such as in operation **812**) may include a step of displacing (such as in operations **1016** or **1017**) the transducer (such as **118**) from the landing zone (such as **120**) at the threshold time. Furthermore, the accelerating step (such as in operation **1010** or **1020**) may include a step of accelerating the data storage disc (such as **108**) at the final acceleration rate between the threshold time and a final predetermined time corresponding to when the rotational velocity of the disc (such as **108**) reaches the final rotational velocity.

In accordance with other embodiments, the accelerating step (such as in operation **800**) may include steps of accelerating (such as in operation **1010**) the data storage disc (such as **108**) at the second acceleration rate from the first predetermined rotational velocity to a second predetermined rotational velocity and accelerating (such as in operation **1020**) the data storage disc (such as **108**) at one or more next acceleration rates from the second predetermined rotational velocity to the threshold rotational velocity if the second predetermined rotational velocity does not equal the threshold rotational velocity. Furthermore, the accelerating step (such as in operations **1010** or **1020**) may include steps of accelerating (such as in operation **1010** or **1020**) the data storage disc (such as **108**) at the third acceleration rate from the threshold rotational velocity to a second predetermined rotational velocity and accelerating (such as in operation **1010** or **1020**) the data storage disc (such as **108**) at one or more next acceleration rates from the second predetermined rotational velocity to the final rotational velocity if the second predetermined rotational velocity does not equal the threshold rotational velocity.

The present invention may also be viewed as a program storage device readable by computer tangibly embodying a program of instructions executable by the computer system to perform a method (such as in operation **800**) for increasing rotational velocity of a data storage disc (such as **108**) in a disc drive (such as **100**).

The present invention may also be viewed as a disc drive (such as **100**) having a data storage disc (such as **108**) rotably mounted to a base plate (such as **102**) and operable to spin at a rotational velocity and an actuator arm (such as **114**) mounted on the base plate (such as **102**) adjacent the disc (such as **108**). The disc drive (such as **100**) includes a transducer (such as **118**) attached to the actuator arm (such as **114**) such that the transducer (such as **118**) is operable to move over a surface of the disc (such as **108**). The transducer (such as **118**) is preferably parked on a landing zone (such as **120**) on the surface of the disc (such as **108**). The disc drive (such as **100**) also includes a means (such as **806** and **808**) for accelerating the data storage disc (such as **108**) at multiple acceleration rates from an initial rotational velocity to a threshold rotational velocity and means (such as **812**) for moving the transducer (such as **118**) from the landing zone (such as **120**) to a data region (such as **304**) on the disc (such as **108**) at the threshold rotational velocity. The threshold rotational velocity may be a final rotational velocity creating and maintaining an air bearing between the transducer (such as **118**) and the surface of the disc (such as **108**) as the transducer (such as **118**) radially traverses across the disc (such as **108**) between an inner diameter (such as **136**) and an outer diameter (such as **138**) in accordance with an embodiment of the invention. The threshold rotational velocity may also be an early exit velocity creating an air bearing between the transducer (such as **118**) and the surface of the disc (such as **108**) as the transducer (such as **118**) exits the landing zone (such as **120**) and accesses the data region (such as **304**) in accordance with an alternative embodiment of the invention.

It will be clear that the present invention is well adapted to attain the ends and advantages mentioned as well as those inherent therein. While a presently preferred embodiment has been described for purposes of this disclosure, various changes and modifications may be made which are well within the scope of the present invention. For example, the multi-phase acceleration procedure may be used to retract a read/write head from a data region to a landing zone or a load/unload ramp during disc drive power down. Furthermore, the multi-phase acceleration procedure may apply only two varied acceleration steps to the disc, with the second stage remaining a constant acceleration until the final rotational velocity is attained in the rotational

-33-

velocity of the disc. Additionally, the read/write head may exit a landing zone at a predetermined

time corresponding to a desired early exit velocity. As such, determination of whether the head is

to leave the landing zone may be based upon this predetermined time, which represents that the

current rotational velocity has reached the desired early exit velocity. Numerous other changes

5   may be made which will readily suggest themselves to those skilled in the art and which are

encompassed in the spirit of the invention disclosed and as defined in the appended claims.